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BENCH DEVELOPMENT ALONG THE REGULATED, LOWER RIVER DEE, UK

SHI CHANGXING[1], GEOFFREY PETTS[2] AND ANGELA GURNELL[2]*

[1] *Institute of Geography, Chinese Academy of Sciences, Beijing, China*
[2] *School of Geography, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*

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ABSTRACT

Channel change to regulated flows along large lowland rivers with cohesive bank materials has been investigated on the lower Welsh Dee, including the tidally influenced reach. Reduction of channel width has involved the formation of a 5–40 m wide discontinuous bench, often linking 'point' and 'concave' locations. Map evidence shows that wide benches occur where historically the channel had migrated laterally; narrow benches were found at stable channel locations. Auger cores of the bench deposits clearly differentiated the two contrasting depositional environments within meandering rivers: 'point bench' and 'concave bench'. Around an individual bend a morphologically continuous bench showed a gradient in sediment characteristics from coarser sediments (point locations) to finer organic deposits (concave locations); it also showed a topographic gradient, gaining 0·5 m in elevation around the bend suggesting that bench accretion at concave locations is faster than at point locations in fluvially dominated reaches. Such patterns are suggested to have important implications for riparian ecosystems. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: channel change; flow regulation; point bench; concave bench; sedimentation

INTRODUCTION

Studies of river channel changes have advanced over the past three decades to apply models of process–form relationships to the management of contemporary human impacts and the restoration of river channels impacted by past human activities (e.g. Calow and Petts, 1994; Gurnell and Petts, 1995; Thorne *et al*., 1997). The effects of river regulation have been a major focus for research (e.g. Petts, 1984; Brookes, 1994; Gore, 1994; Brookes and Shields, 1996), and the role of geomorphological processes in sustaining or restoring the biodiversity of regulated-river corridors has attracted much recent attention (Naiman and Décamps, 1990; Petts, 1996, 1997).

Along many rivers the effects of regulation are lowered flood magnitudes, reduced sediment loads and/or a decline in the grain size of the sediment load. One widely reported response to such changes is a reduction of channel width especially in former braided sectors which have changed to single-thread channels (e.g. Williams and Wolman, 1983; Petts *et al*., 1989). Along natural single-thread channels, the mechanisms of width reduction to flow regulation have been shown to be complex (Petts, 1979) and influenced by: (i) local sediment sources; (ii) bank materials; and (iii) the dimensions of the channel at the time of regulation (Petts and Pratts, 1983). However, the mechanisms of channel width reduction along large lowland rivers have received relatively little attention in comparison to progress on the typically more dynamic, upland gravel-bed rivers. In central and southern UK, many rivers are laterally stable, having more or less sinuous courses bounded by cohesive alluvium, often dating to the medieval period of land-use change and floodplain accretion (e.g. Brown, 1995; Large and Petts, 1996). In such cases, width adjustment to flow regulation occurs within the confines of the existing channel and is manifest by lateral benches, having a surface elevation lower than the level of the adjacent floodplain, creating a two-stage channel that is often spatially discontinuous (Petts, 1979; Brookes, 1992).

* Correspondence to: Professor A. Gurnell, School of Geography, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

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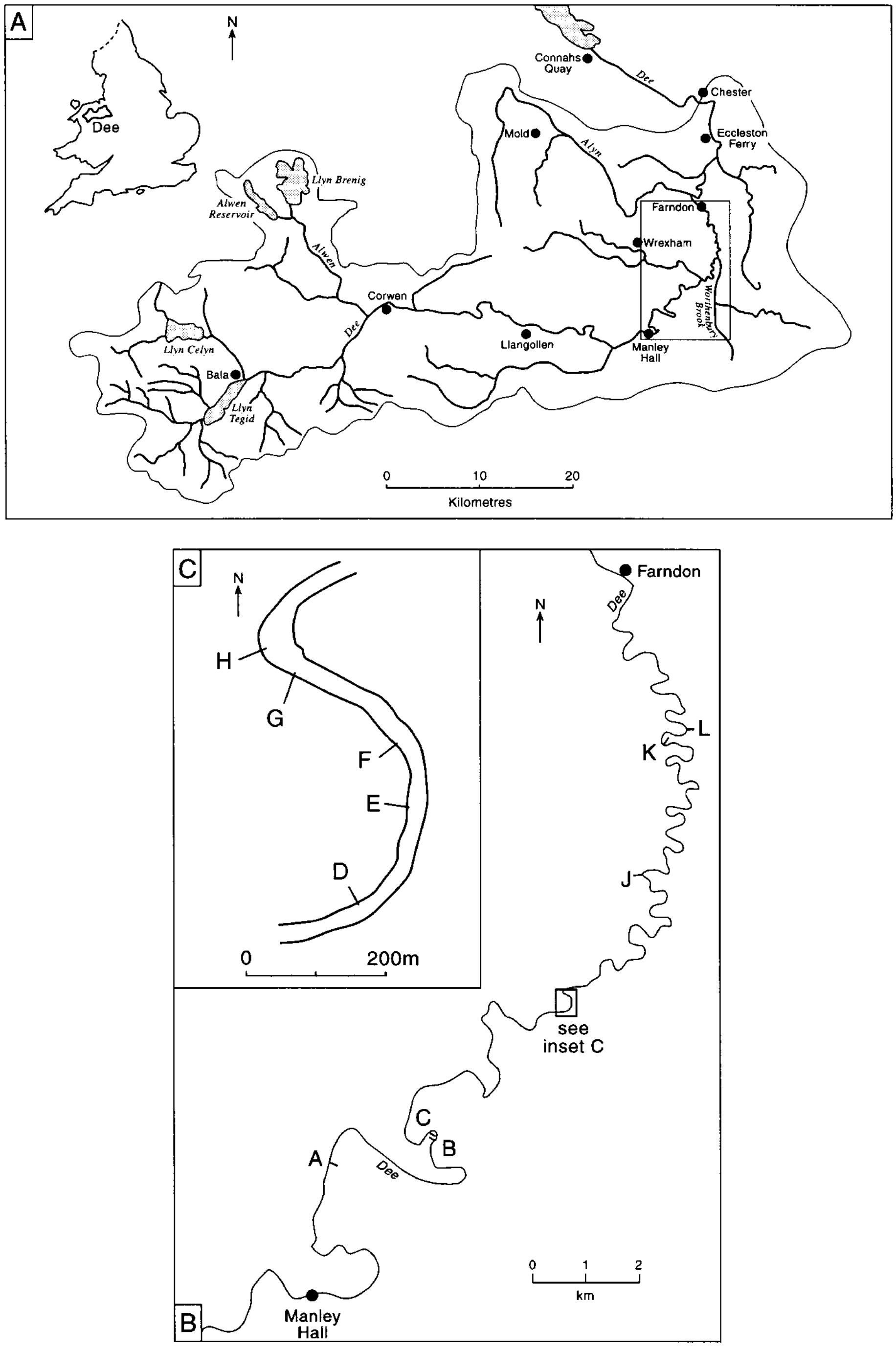

Figure 1. Location maps: (A) the Dee catchment; (B) the lowland sector; and (C) the detailed study reach. The study benches are labelled alphabetically in a downstream direction

Benches may be classified according to their location within the channel as: (a) point or (b) concave (counterpoint) benches within meandering rivers; (c) marginal benches along straight reaches; and (d) tributary confluence benches. The last type is common along upland regulated streams (Petts, 1984). The contrasting depositional environments of point and concave benches have been demonstrated along natural meandering rivers (Lewin, 1983; Nanson and Page, 1983) but their contribution to channel change along lowland regulated rivers has not been assessed. This paper examines the nature of channel width reduction and associated bench forms along a lowland sector of a regulated, single-thread river, the River Dee, North Wales, UK.

THE STUDY AREA

The catchment area of the River Dee, to the head of its estuary at Chester Weir, is 1816 km^2 (Figure 1A). Annual average rainfall varies from 2500 mm in the mountains above Bala to 600 mm near Chester, generating a daily mean river flow of approximately 37 $m^3 s^{-1}$. Since the early 19th century, the river has been subject to increasing flow regulation. The main hydrological changes relate to the closure of the impounding Alwen Reservoir (capacity $15 \times 10^6 m^3$) in the 1920s; the regulation of Bala Lake in the 1950s (resulting in $18 \times 10^6 m^3$ controllable water storage); the completion of the regulating reservoir Llyn Celyn (capacity $81 \times 10^6 m^3$) in 1964; and the completion of the regulating reservoir Llyn Brenig (capacity $60 \times 10^6 m^3$) in 1979. Thus, reservoir regulation of river flows has developed progressively through this century, but has been particularly strong since the completion of Llyn Celyn in 1965. The reservoirs regulate flow: (i) to control flooding; (ii) to support total water abstractions of $0{\cdot}892 \times 10^6 m^3$ per day, the abstraction sites being mainly located downstream of the reach on the River Dee discussed in this paper, and (iii) to maintain a minimum residual flow at Chester Weir. A review of the River Dee regulation is provided by Lambert (1988).

Regulation by the reservoirs has increased low flows and decreased high flows which are fully discussed in Gurnell *et al.* (1994). In summary, analysis of river flow records from 1938 to 1992 for the Erbistock/Manley Hall gauging station (Figure 1A, B), located immediately upstream of the study reach, has identified two trends. First, monthly instantaneous maximum flows show a steady decline in their annual mean and standard deviation over the entire record. Using the Gumbel (EVI) probability distribution, it was found that the magnitude of the mean annual flood fell from 269 to 231 $m^3 s^{-1}$ between 1946–1963 and 1965–1992, a reduction of 14 per cent. The annual maximum and minimum of the monthly instantaneous maximum flows decreased in variability after the mid-1960s with the magnitude of the former declining and the latter increasing over the same time period. Second, the range in mean monthly flows shows decreasing variability through the period. The annual mean, median and maximum of the mean monthly flows fluctuate around a relatively stable level through the 1938–1992 period, but there is a marked increase in minimum mean monthly flows, particularly after the mid-1960s. Prior to 1966 the minimum annual mean monthly flow frequently fell below 5 $m^3 s^{-1}$, but since 1966 a flow below 8 $m^3 s^{-1}$ has been rare.

In addition to the temporal impact of flow regulation on the study reach of the Dee, there is an additional spatial influence on water levels and flow velocities induced by downstream tidal levels and a backwater from Chester Weir (crest level approximately 4·4 m AOD). Unsteady flow conditions occur in the Lower Dee for up to 30 per cent of the time as a result of tidal overtopping of the weir. The effects range from minor pulses in river levels caused by slight overtopping of the weir to the effects of the highest spring tides causing flow reversal as far as Farndon (just downstream of the study reach, Figure 1A, B) and backwater effects occur for a further 10 km upstream (Weston, 1979).

The effects of these hydrological influences upon channel form have been elaborated by Gurnell *et al.* (1994) and Gurnell (1997a). These describe GIS-based analyses of planform change on the study reach of the River Dee using digitized boundaries from historical maps (1876, 1897, 1909, 1949 and 1979) and air photographs (1946, 1951, 1966, 1974, 1985 and 1992) at approximately 1:10 000 scale, representing the period of the last 115 years (see, for example, Figure 7A). In addition, Gurnell (1997b) has analysed

spatial trends in the channel cross-sectional geometry based upon a survey undertaken by the river authority in 1973. Two important conclusions supported the advancement of the present study.

1. The channel planform has been rather stable over the historical period and there is a spatial trend of increasing positional stability and decreasing channel width down the study reach. This can be associated with decreasing stream power down the reach as a result of decreasing bed slope and the increasing influence of the backwater from Chester Weir, and from high tidal levels overtopping the weir crest.
2. Analyses of minima in the width:mean depth ratio within the channel cross-section have further elaborated the spatial trend and have identified three distinct morphological levels which appear to be associated with particular properties of the flow and sediment transport regime. Level 1 (the overtopping level) defines a channel which becomes narrower (46 to 38 m) and deeper in a downstream direction, so maintaining an approximately constant cross-sectional area sufficient to accommodate the 1·5 to 2·33 year return period flood. Various modelling approaches suggest that Level 2, located within the channel defined by Level 1, may be associated with a morphological adjustment to a change in the dominant discharge for sediment transport as a result of flow regulation. The average width of the channel at Level 2 is 33 m. The lowest level, Level 3 (average width 27 m), occurs within the channel defined by Level 2, and is only identified within cross-sections located within the downstream part of the reach. This is believed to result from the influence of the Chester Weir backwater and tidal overtopping of the weir on both flow and sediment transport.

The present study focused on a 20 km reach (Figure 1B) which includes three sectors defined by Gurnell (1997a): (i) a fluvially dominated upstream sector; (ii) a sector dominated by fluvial floods but also affected by spring tides; and (iii) a lower sector dominated by the backwater effects of Chester Weir. The paper explores the characteristics of benches associated with Level 2, to explore further the morphological impacts of flow regulation. The paper undertakes the following analyses.

1. Sediment profiles were obtained from benches (equivalent to the limits of the Level 2 channel) located along the study sector of the lower Dee. Bank profiles are used to illustrate the form of the benches and the location of the sediment profiles with respect to the benches. Where information from historical sources is available, the profiles are placed in the context of the temporal development of the benches.
2. Analyses of aggregate and depth-profiled particle size and organic content of cores of the bench sediments are presented and are compared with the character of samples taken from the main floodplain terrace (i.e. Level 1) and from the bases of the bench profiles. The process significance of the results is discussed.

SAMPLING DESIGN

Along the Dee, benches occur as both isolated and connected point and concave benches associated with meander bends, and narrow, sometimes discontinuous, marginal benches along straighter reaches. Examples of the two main types of bench were selected for study (Figure 1B), together with a single example of a marginal bench: A (marginal bench); C, D, E, F, K (point benches); and B, G, H, J, L (concave benches). No tributary confluence benches were identified. The majority of the sampled benches (A, B, C, D, E, F, G, H) are located within the entirely fluvially influenced sector of the lower Dee. Transects D to H, inclusive, form a sequence from point to concave bench locations around a single bend in the river (Figure 1C). Concave bench J is located on a bend within the sector of river affected by the backwater associated with high spring tides, whereas K and L are point and concave benches, respectively, within the sector affected by both the backwater from Chester Weir and high spring tides.

A single sediment core was taken near the highest point along a transect across the bench at sites A, B,

Table I. Summary data on benches surveyed along the lower Dee (locations are shown in Figure 1)

Bench	Width (m)	Maximum elevation* (m)	Type†
A	5	0·5	m
B	10	1·3	c
C	9	1·1	p
D	6	0·7	p
E	20	0·8	p
F	7	0·7	p
G	42	1·1	c
H	23	1·2	c
J	23	0·4	c
K	5	3·4	p
L	13	0·6	c

* Maximum elevation is estimated in relation to the arbitrary datum of water level during the 36 h period of the topographic survey
† Benches were classified according to location as marginal (m), point (p) or concave (c)

C, D, F, H and K; two cores were taken from benches G and L; and three and four cores described transects across the point bench at site E and the concave bench at site J, respectively. Wherever possible, bench cores were augered to a level at which there was a clear discontinuity in the sediment profile, assumed to represent the bed of the channel prior to bench aggradation.

A total of 178 samples, representing bench core segments of approximately 15 cm in length, were obtained from the 18 bench sediment cores. The precise depth range of each sample was recorded at the time of sampling. A further 10 samples were taken from the base of bench cores, where sediments likely to be representative of the basement deposits were encountered. All of the samples were processed by dry-sieving down to 2 mm, wet-sieving to 0·125 mm, and by Coulter LS analyser to obtain the particle size distribution below 0·125 mm. Organic content was determined by loss-on-ignition.

RESULTS

Table I summarizes the bench characteristics and Figure 2 shows the 11 bank profiles. At the sector scale, there are differences in bench form between the fluvially dominated part and the downstream reach influenced by backwater effects. Within the former, point benches are typically 5 to 18 m wide and concave benches are 20 to 40 m wide. In contrast, site K, downstream, has a steep bank profile representative of the more restricted planform change. Differences also occur at the reach scale. The maximum elevation of the bench around bend D–H is between 0·7 and 1·2 m above the ambient water level, being lowest at D and increasing progressively in height downstream. This suggests that the rate of bench accretion is faster in concave locations than at point sites. This is supported by comparison of point bench C and concave bench B. Comparison of profiles at sites K and L, however, suggests that in the narrower, tidally influenced reaches point benches develop by the draping of sediment on the existing bank, growing laterally, rather than vertically, with time.

The contrast between the different depositional environments is well illustrated using a C–M type image (Passega, 1964), based on an index of the coarsest fraction, d_5 (C) and the median (M) (Figure 3). The plot differentiates samples of, respectively, the bed deposits before bench building; point and marginal bench deposits; and concave bench deposits. Differences in the character of aggregated samples in each core were explored using cluster analysis on the particle size and organic content in each profile. This analysis (Figure 4) clearly confirms the differentiation and classification of the point and concave deposits, and shows that the concave benches (i.e. G2 to L2, the left cluster) are less variable in character

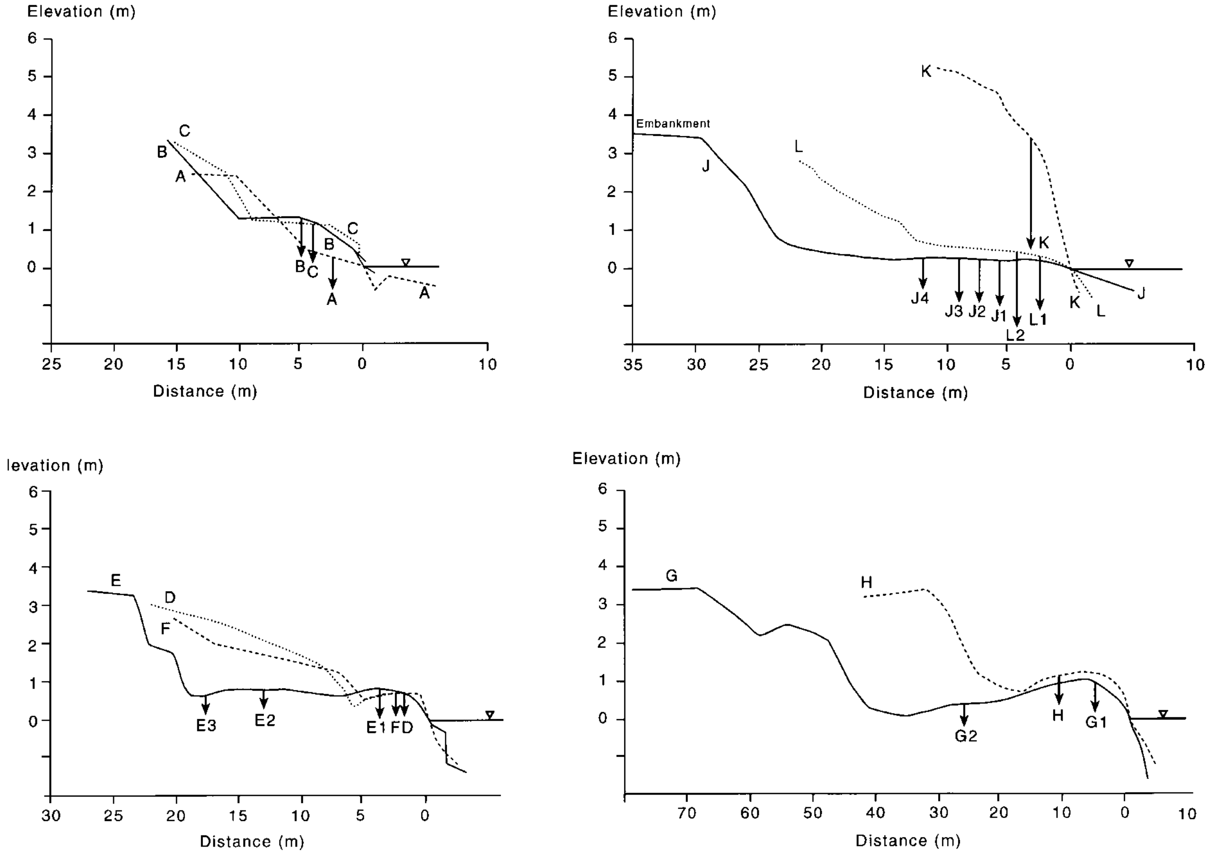

Figure 2. Profiles of the study sites locating the sediment cores. Profiles are plotted with respect to an arbitrary vertical datum and are compared using the position of the water's edge at the time of survey which was completed within 36 h during a period when there was no tidal overtopping of Chester weir and the river flow was in slow recession

than the point benches (i.e. F to K, the right cluster). The marginal bench, sample (A), was grouped with the point-bench deposits (C, D, E, F, K). There was no downstream pattern within either of the two groups. Vertically accreting bench C, located in the upstream part of the reach, was grouped with the laterally accreting bench K located in the tidally influenced zone.

Bulk sediment characteristics

Table II provides descriptive statistics for the particle size distributions of the 178 bench samples grouped according to bench type. Average indices of the particle size distribution and organic content of each bench profile above the basement sediment discontinuities were derived using a thickness-weighted average method to aggregate information from the samples within each of the profiles. The concave and point bench types are very clearly distinguished by the fifth percentile (d_5), an index of the coarsest particles in the deposit. Other indices including the mean particle size also provide quite good discrimination between bench types. The point bench samples exhibit a similar grain size (mean = 0·061 mm) to the marginal bench samples (mean = 0·058 mm), which are in turn coarser than concave bench samples (mean = 0·020 mm). The more variable and coarser grain sizes associated with the point bench samples (see also Figure 3) suggest that the flow conditions associated with the depositional environment for this type of bench are more variable than for concave situations. In particular, the consistently coarser particle sizes associated with the d_5 index (point bench value of

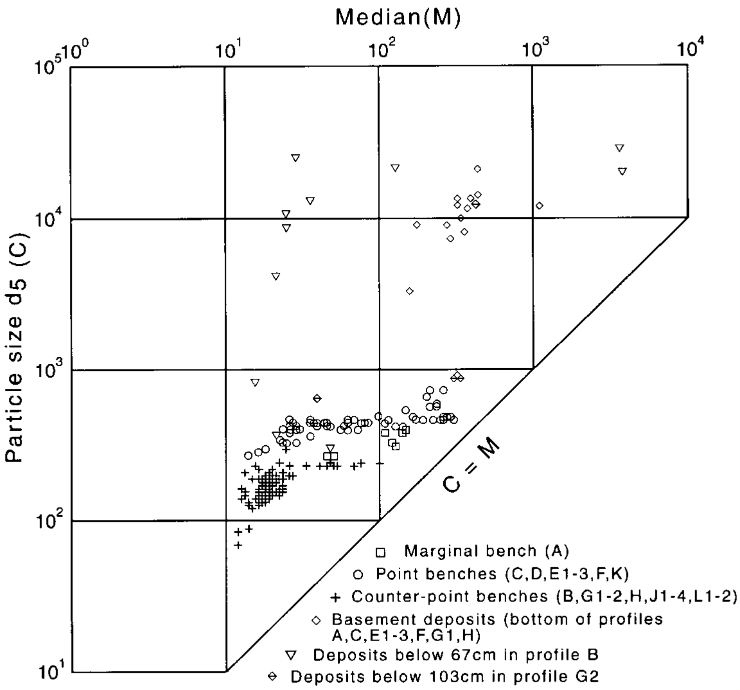

Figure 3. C–M plot using median grain size (mm) against the fifth percentile (percentage coarser than) showing patterns of sediments deposited in different environments for all samples from the different benches on the River Dee

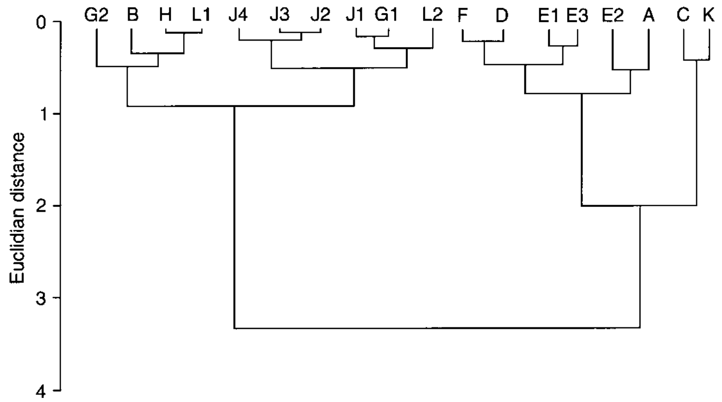

Figure 4. Cluster analysis of sedimentological data from the 18 cores. Note that the entire cluster to the left (i.e. G2 to L2) comprises concave benches and the entire cluster to the right (i.e. F to K), with the exception of marginal bench A, comprises point benches

Table II. Summary characteristics of the particle size distributions of the different bench types, based on 178 samples from 15 cm segments of the sediment cores (descriptive measures use standard Folk and Ward (1957) statistics). Only those samples from above any basal gravelly sand are included

Bench type	Concave	Point	Marginal
Sample size	100	71	7
Mean (Ø (mm))	5·61 (0·020)	4·03 (0·061)	4·10 (0·058)
Standard deviation (Ø)	2·18	2·38	2·22
Skewness (Ø)	0·07	0·29	0·51
Kurtosis (Ø)	0·90	0·98	0·85
50th percentile (Ø (mm))	5·76 (0·018)	4·16 (0·056)	3·00 (0·125)
5th percentile (Ø (mm))	2·53 (0·173)	1·51 (0·351)	1·59 (0·332)
Organic content (%)	5·8	4·0	5·3

Percentiles are percentage coarser than

0·351 mm compared with 0·173 mm for concave benches and 0·332 mm for the marginal bench) reflect the generally higher energy environment associated with point bench building.

Vertical changes in bench profiles

Table III summarizes data for each of the 18 cores. The basement deposit (0 cm in Table III) at most sites has a d_5 of over 10 mm.

(1) The point bench profiles show a marked basal discontinuity and a uniform grain-size distribution above, with d_5 ranging from *c.* 0·50 mm immediately above the discontinuity to *c.* 0·45 mm near the surface, and the mean varying from *c.* 0·065 mm to *c.* 0·050 mm. Organic matter forms less than 7 per cent of the deposit. Marginal bench A shows a coarsening upwards with the mean and d_5 grain sizes increasing from 0·047 mm to 0·082 mm and 0·330 mm to 0·435 mm, respectively. The organic content at this site is low throughout. Only site K, within the tidal backwater influence, displays a different profile described by little variation in d_5 (*c.* 0·450 mm) but with a marked coarsening upwards in the mean (from 0·044 mm to 0·250 mm; see Figure 6). The vertical extent of this point bench is greater than in the other situations, and the deposit forms a drape over the bank face dominated by well-sorted medium sands.

(2) Profiles from the concave bench deposits also display uniform mean particle sizes that do not change greatly in the vertical profile. The d_5 of the deposits shows slight fining upwards in most profiles (*c.* 0·25 to 0·18 mm). Mean grain sizes decrease upwards from *c.* 0·04 to 0·02 mm and organic content rises from less than 5 to up to 17 per cent near the surface.

Thus, around a single bend (Figure 5 – see Figure 1C for site locations) there is a clear pattern of sedimentation. The basement gravelly sand deposit increases in size from a mean of 0·189 mm at site E1, a point bench, to 0·500 mm at G1 before decreasing again to 0·088 mm at H. The fifth percentile of this basal deposit varies from 11·3 mm at E1, to 22·6 mm at F, 13·9 mm at G1 and 3·48 mm at H. At all sites a clear discontinuity exists between the basement and the organic, sandy-silt deposit above. The overlying deposit is much finer than the basement with the mean of the surface deposits decreasing from 0·051 mm at E1, to 0·041 mm at F, and to 0·021 mm at G1 and H. The respective d_5 values are 0·435 mm at E1, 0·467 mm at F, 0·177 mm at G1 and 0·144 mm at H. These differences relate to location around the meander bend rather than to any difference in elevation. The concave bench sites generally have higher organic matter content (*c.* 8 per cent) than the point bench sites (*c.* 5 per cent).

At sites with wide benches (e.g. point bench E and concave bench G, Figure 6), map evidence shows

Table III. Summary data for sediment profiles

(A) Point and marginal benches

	A	C	D	E1	E2	E3	F	K
Core depth (m)	1·25	1·10	0·6	1·10	1·25	1·6	1·6	3·0
Mean (Ø (mm))								
Surface	3·6 (0·082)	3·8 (0·072)	4·2 (0·054)	4·3 (0·051)	4·5 (0·044)	4·3 (0·051)	4·6 (0·041)	2·0 (0·250)
+ 15 cm	4·4 (0·047)	3·2 (0·109)	5·0 (0·031)	4·2 (0·054)	3·6 (0·082)	4·0 (0·063)	4·8 (0·036)	4·5 (0·044)
0 cm	0·5 (0·707)	0·2 (0·871)		2·4 (0·189)	1·0 (0·500)	1·6 (0·330)	1·2 (0·435)	
d_5 (Ø (mm))								
Surface	1·2 (0·435)	1·2 (0·435)	1·2 (0·435)	1·2 (0·435)	1·2 (0·435)	1·2 (0·435)	1·1 (0·467)	1·1 (0·467)
+ 15 cm	1·6 (0·330)	0·6 (0·660)	1·3 (0·406)	1·0 (0·500)	1·0 (0·500)	1·0 (0·500)	1·0 (0·500)	1·2 (0·435)
0 cm	–2·6 (6·06)	–3·8 (13·9)		–3·5 (11·3)	–3·5 (11·3)	–3·5 (11·3)	–4·5 (22·6)	
Organics (%)								
Surface	5·4	7·0	4·5	5·0	5·6	4·5	4·0	2·0
+ 15 cm	5·5	3·5	3·0	10·0	3·2	8·0	2·8	3·0
0 cm	4·5	2·5		3·5	3·0	2·1		

(B) Concave benches

	B	G1	G2	H	J1	J2	J3	J4	L1	L2
Core depth (m)	2·20	1·65	1·55	2·85	1·25	1·15	0·75	0·4	3·0	2·5
Mean (Ø (mm)										
Surface	5·6 (0·021)	5·6 (0·021)	5·5 (0·022)	5·6 (0·021)	5·5 (0·022)	5·5 (0·022)	5·5 (0·022)	5·7 (0·019)	5·8 (0·018)	5·8 (0·018)
+ 15 cm	4·9 (0·033)	4·8 (0·036)	2·6 (0·165)	5·5 (0·022)	5·3 (0·025)	5·8 (0·018)	5·9 (0·017)	6·1 (0·015)	5·8 (0·018)	4·9 (0·033)
0 cm		1·0 (0·500)	1·0 (0·500)	3·5 (0·088)						
d_5 (Ø (mm))										
Surface	2·2 (0·218)	2·5 (0·177)	2·6 (0·165)	2·8 (0·144)	2·6 (0·165)	2·7 (0·154)	2·6 (0·165)	2·6 (0·165)	2·8 (0·144)	2·5 (0·177)
+ 15 cm	2·0 (0·250)	1·0 (0·500)	0·2 (0·871)	2·5 (0·177)	2·0 (0·250)	2·1 (0·233)	2·2 (0·218)	2·8 (0·144)	2·6 (0·165)	2·1 (0·233)
0 cm		–3·8 (13·9)	–3·8 (13·9)	–1·8 (3·48)						
Organics (%)										
Surface	17	8	15	9	12	10·5	7·5	5·4	12	16
+ 15 cm	8	2	1	10	2	2·5	2·5	4·5	4·5	4·5
0 cm		2	1	5						

'0 cm' refers to the basement gravelly-sand or, if not encountered, the lowest point in the profile. Depths (i.e. + 15 cm) refer to distance above the basal discontinuity or above the lowest point in the profile

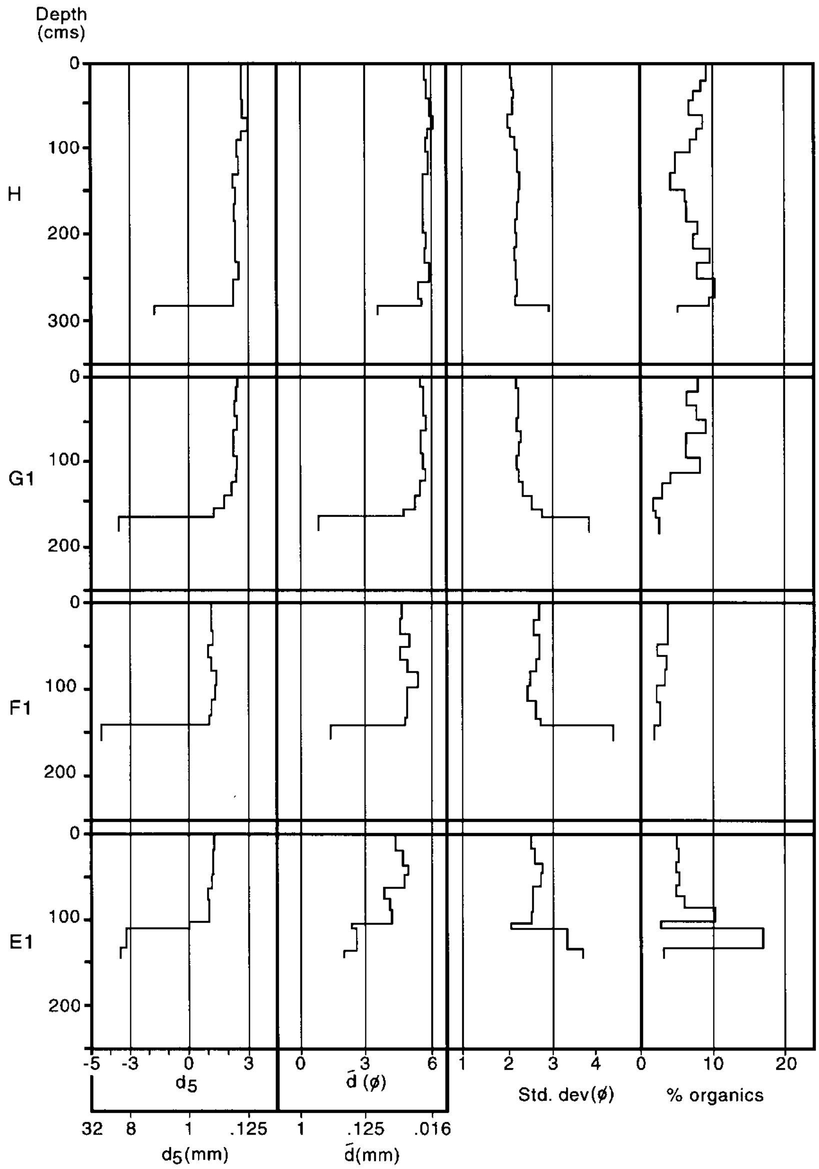

Figure 5. Vertical sediment profiles from sites around the meander bend (E–H; Figure 1)

that bench growth involved the formation of a gravelly sand bar which evolved into an island, and the infilling of the secondary channel, connecting the bar/island to the former bank (see e.g. Figure 7A). Sediments filling the secondary channel initially are finer than the sediments forming the bar/island with a minimum mean grain size of 0·03 and 0·012 mm at E3 and G2, respectively, but at both sites the deposits coarsen upwards and the island/channel have the same grain size distribution towards to the surface. However, the pattern of organic matter accumulation differs between the point and concave sites. The point bench sites (E1 and E3) show a basal accumulation of organic matter above which the organic content stabilizes at a level of about 5 per cent towards the surface. In contrast, both of the concave sites (G1 and G2) show a marked increase in organic matter content towards the surface of the profiles, with highest levels (15 per cent) in the deposits filling the backwater (the former channel: G2).

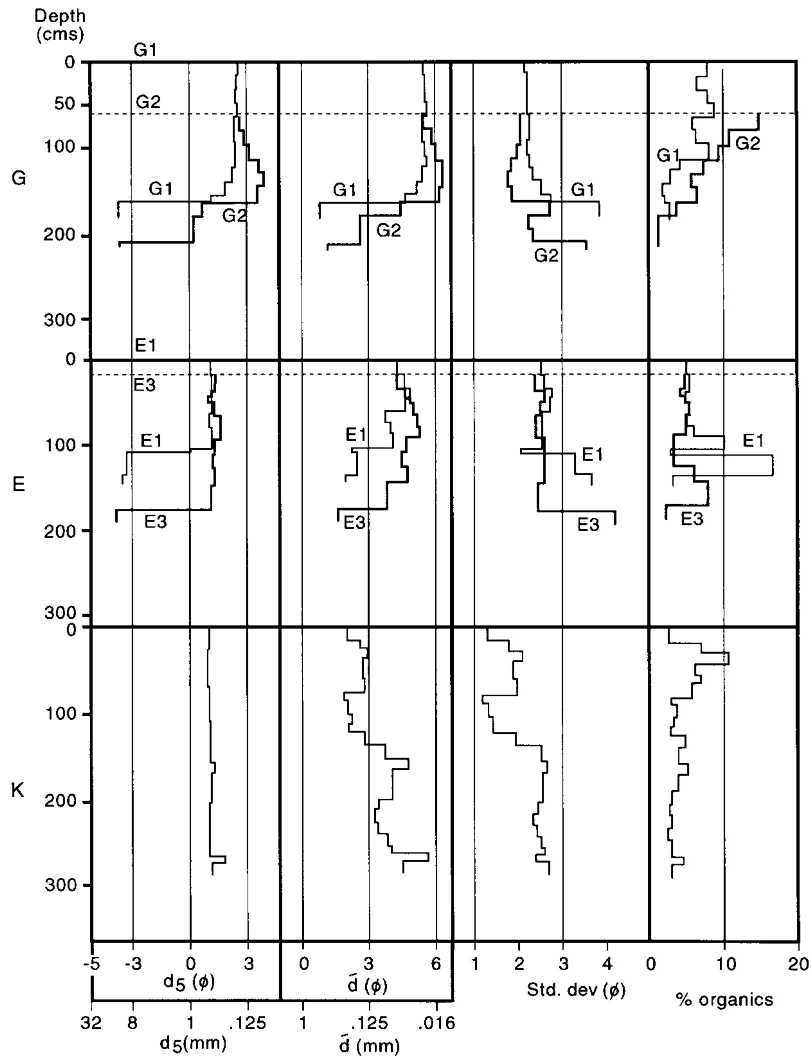

Figure 6. Vertical sediment profiles for selected sites: concave (G); point (E); and (K), the latter being influenced by tidal backwaters

DISCUSSIONS AND CONCLUSIONS

Along the lowland study sector of the River Dee, located over 50 km from upstream reservoirs, clear adjustments in channel planform have occurred, particularly in the major period of flow regulation which commenced in the 1960s. The adjustment in planform has, in large part, been achieved by the development of predominantly point and concave benches within the old channel. A strong temporal pattern was defined within the historical data (Gurnell *et al.*, 1994; Gurnell, 1997a,b), where the most notable changes seem to have been a channel width reduction of approximately 3–4 m in the upstream part of the sector since the 1960s (based on air photograph interpretation of the permanent vegetation limit). In the downstream part of the sector, channel width reduction appears to have occurred later (since the 1970s to 1980s), but to have been of similar magnitude to the upstream reduction (approximately 3 m). Lateral shifting of the channel, to a variable degree, has accompanied narrowing and has led to the creation of benches of up to 40 m in width (e.g. Figure 2).

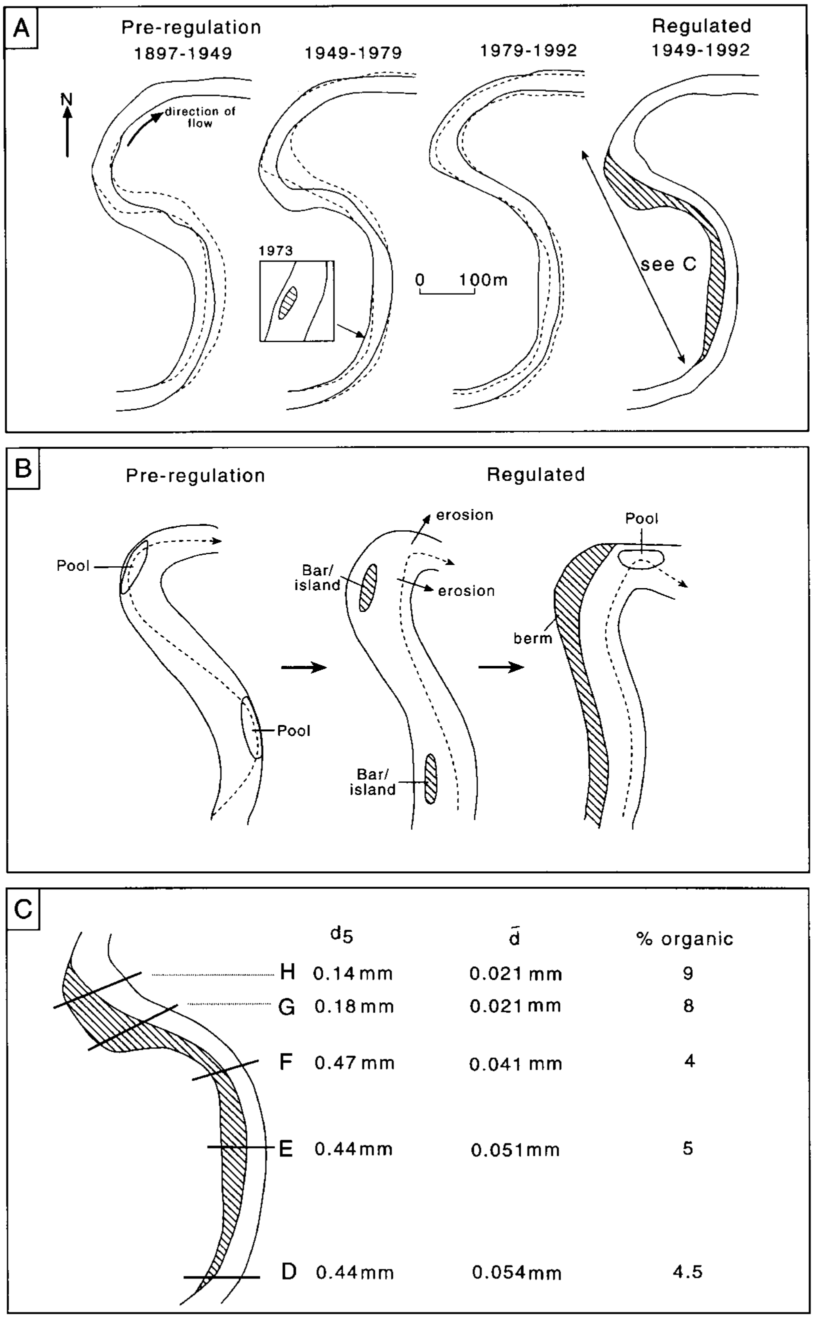

Figure 7. Bench development. (A) Channel changes within the detailed study reach on the Dee (D–H) derived from maps (the location of the bench depicted in (C) is indicated on the 1949–1992 change map). (B) A model of channel change to flow regulation in lowland rivers (after Chien, 1985). (C) The pattern of sediment characteristics along a gradient from point to concave bench, around the meander bend indicated in (A) on the 1949–1992 change map (sites are D–H on Figure 1C).

Analyses of the particle size and organic content parameters clearly differentiate point and concave bench deposits. Concave bench deposits consist mainly of uniform sandy silts (mean 0·02 mm and d_5 of 0·20 mm). Point benches are coarser, dominated by silty sands (mean 0·06 mm and d_5 of 0·45 mm), and display more variable characteristics. The fluvially dominated point benches differ markedly from those influenced by backwater effects (e.g. K, Figure 6) but concave benches have similar characteristics throughout the fluvially dominated and backwater-dominated sectors of the lower River Dee. Concave bench deposits are not only higher in organic content than point benches but also show a vertical increase in organic content above the basement. The organic matter content of the sediments varies through the profiles (e.g. profile H, Figure 5).

The organic content of the deposits depends on several factors including: the density and character of the vegetation growing on the benches; the amount of organic material delivered from upstream or from the banks above the benches; the overall sedimentation rate; and the rate of decomposition of organic material in the bench deposits. Plants growing on benches not only provide organic remains but also help to trap organic material transported by the flow. In general, plant growth becomes more vigorous as the bench surface builds up above the low-flow water level. As a result, many of the profiles show an increasing organic content towards the surface of the bench deposits. This is particularly noticeable for the profiles from concave benches, where the counter-rotational eddying can enhance the accumulation of organic materials. As a result, the surface layers of the concave benches have a higher organic content than those of point benches, but with increasing depth, and thus movement towards levels that would have been more frequently inundated during deposition, the contrasts in organic content are less well defined.

The classic description of concave benches on the Murrumbidgee, Australia (Nanson and Page, 1983) describes deposits of fine sandy mud and muddy sand, fining upwards (mean 0·25 mm to 0·008 mm) overlying a basement deposit of well sorted medium sand. Adjacent point bars had mean particle sizes of 1 mm to 0·25 mm and almost no silt and clay. Nanson and Page (1983) concluded that concave benches are common along natural rivers where rates of channel migration are low and where stream power barely exceeds that required to erode cohesive channel banks. Such conditions are associated with the development of meanders with abruptly curving bends. These conditions tend to characterize confined meandering channels that migrate along the valley wall (Lewin, 1983), which is an inherent process of planform change along lowland rivers. The process may be especially important for channel adjustment to reduced flood flows. Indeed, Nanson and Page (1983) suggest that concave benches may be common along underfit streams.

Along the meandering, lowland River Dee, channel adjustment to flow regulation has involved the reduction of channel width by the development of 5 to 42 m wide benches having an elevation of about 2·5 m below that of the former floodplain. However, this study shows that bench building involves different processes at point and concave locations producing marked differences in the sedimentology of the benches. Thus, around a meander bend, from D to H (Figure 1C) there is a clear pattern of development, with coarser silts and sands characterizing the point bench setting and finer organic silts and clays characterizing the concave locations. Superposition of three maps of the bend (1949, 1979 and 1992; Figure 7A) shows a tendency towards local reduction in sinuosity, resulting in significant concave deposition (sites G and H). A similar case was observed at site J (Figure 1B). At concave locations the mode of bench building may typically involve a phase of bar/island building in a manner similar to that described by Page and Nanson (1982). Maps and sediment data indicate that at transects E and G (Figures 2 and 5) bench building involved bar building with a small secondary channel close to the original channel bank.

The above supports a general model for channel change to flow regulation in single-thread, sinuous channels (Chien, 1985; Figure 7B). The sudden change in flow and sediment regimes coincident with dam closure induces channel adjustment that may be categorized as two phases. First, bars, building into islands, form by the deposition of bedload at wide sections. Coarser sediments deposit along convex banks (point bench locations) than along concave banks (concave bench locations). Deposition at the

latter is induced by the movement of the thalweg away from the outside of the bend towards mid-channel or, in extreme cases (e.g. G–H on the Dee), to the convex bank leading to a progressively overtightened bend and erosion of the point bar. This probably reflects the influence of the developing island on roughness. Second, flow separation at the concave bank creates a region of gently circulating flow where the deposition of fine grained sediments leads to the development of the concave bench (Hodskinson, 1996). On the Dee, bench development is often along one side of the channel, being limited by erosion at and downstream of the apex of an overtightened bend. Along each bench, the deposits vary in a more or less predictable manner around each geomorphological unit (half a meander wavelength) from silty-sand, through sandy-silt, to organic silt (Figure 7C).

This pattern of bench development is particularly significant for ecological processes within the riparian zone. The grain-size distribution of sediments, as well as elevation (which determines the average duration of inundation) influences the distribution of flora and fauna, and key ecosystem processes such as organic matter decomposition and denitrification (Petts, 1996). Thus, river margin ecosystems may show a patchy, but more or less repeatable pattern along lowland meandering channels. The main site here (Figure 1C) is one focus for a detailed investigation of these ecological processes as part of the European River Margin Systems Programme (ERMAS: DGXII ENV4-CT95-0061) which aims to model the sensitivity of river margin ecosystems to environmental changes at regional and local scales. Preliminary findings of this research are reported in Gurnell *et al.* (1998).

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REFERENCES

Brookes, A. 1992. 'Recovery and restoration of some engineered British river channels', in Boon, P. J., Calow, P. and Petts, G. E. (Eds), *River Conservation and Management*, Wiley, Chichester, 337–352.

Brookes, A. 1994. 'River channel changes' in Calow, P. and Petts, G. E. (Eds), *The Rivers Handbook*, Blackwell Scientific, Oxford, 55–75.

Brookes, A. and Shields, F. D. (Eds) 1996. *River Channel Restoration: Guiding principles for sustainable projects*, Wiley, Chichester.

Brown, A. G. 1995. 'Holocene channel and floodplain change: a UK perspective', in Gurnell, A. and Petts, G. E. (Eds), *Changing River Channels*, Wiley, Chichester, 43–64.

Calow, P. and Petts, G. E. (Eds) 1994. *The Rivers Handbook*, Blackwell Scientific, Oxford.

Chien, N. 1985. 'Changes in river regime after the construction of upstream reservoirs', *Earth Surface Processes and Landforms*, **10**, 143–160.

Folk, R. L. and Ward, A. C. 1957. 'Brazos river bar: a study in the significance of grain size parameters', *Journal of Sedimentary Petrology*, **27**, 3–26.

Gore, J. A. 1994. 'Hydrological changes', in Calow, P. and Petts, G. E. (Eds), *The Rivers Handbook*, Blackwell Scientific, Oxford, 33–54.

Gurnell, A. M. 1997a. 'Channel change on the River Dee meanders, 1946–1992, from the analysis of air photographs', *Regulated Rivers*, **13**, 13–26.

Gurnell, A. M. 1997b. 'Adjustments in river channel geometry associated with hydraulic discontinuities across the fluvial–tidal transition of a regulated river', *Earth Surface Processes and Landforms*, **22**, 967–985.

Gurnell, A. M. and Petts, G. E. (Eds) 1995. *Changing River Channels*, Wiley, Chichester, 442 pp.

Gurnell, A. M., Downward, S. R. and Jones, R. 1994. 'Channel planform change on the River Dee meanders, 1976–1992', *Regulated Rivers*, **9**, 187–204.

Gurnell, A. M., Bickerton, M., Angold, P., Bell, D., Morrisey, I., Petts, G. E. and Sadler, J. 1998. 'Morphological and ecological change on a meander bend: the role of hydrological processes and the application of GIS', *Hydrological Processes*, **12**, 981–993.

Hodskinson, A. 1996. 'Computational fluid dynamics as a tool for investigating separated flow in river bends', *Earth Surface Processes and Landforms*, **21**, 993–1000.

Lambert, A. 1988. 'Regulation of the River Dee', *Regulated Rivers*, **2**, 293–308.

Large, A. R. G. and Petts, G. E. 1996. 'Historical channel-floodplain dynamics along the River Trent', *Applied Geography*, **16**, 191–209.

Lewin, J. 1983. 'Changes of channel patterns and floodplains', in Gregory, K. J. (Ed.), *Background to Palaeohydrology*, Wiley, Chichester, 303–319.

Naiman, R. and Décamps, H. (Eds) 1990. *The Roles of Ecotones in Aquatic Landscapes*, Cambridge University Press.

Nanson, G. and Page, K. 1983. Lateral accretion of fine-grained concave benches on meandering rivers', in Collinson, J. D. and Lewin, J. (Eds), *Modern and Ancient Fluvial Systems*, Special Publication of the International Association of Sedimentologists **6**, 133–143.

Page, K. and Nanson, G. 1982. 'Concave-bank benches and associated floodplain formation', *Earth Surface Processes and Landforms*, **7**, 529–543.

Passega, R., 1964. 'Grainsize representation by C.M. patterns as a geological tool', *Journal of Sedimentary Petrology*, **34**, 830–847.

Petts, G. E. 1979. 'Complex response of river channel morphology subsequent to reservoir construction', *Progress in Physical Geography*, **3**(3), 329–362.

Petts, G. E. 1984. *Impounded Rivers*, Wiley, Chichester.

Petts, G. E. 1996. 'European river margins (ERMAS): an ecological assessment of high-flow needs', *Proceedings RIVERTECH'96*, IWRA, 97–104.

Petts, G. E. 1997. 'The scientific basis of managing biodiversity along river margins', in La Chavanne, J-B. and Juge, R. (Eds), *Biodiversity and Land-water Ecotones*, UNESCO, Paris, 249–266.

Petts, G. E. and Pratts, J. D. 1983. 'Channel changes following reservoir construction on a lowland English river', *Catena*, **10**, 77–85.

Petts, G. E., Moller, H. and Roux, A. L. (Eds) 1989. *Historical Changes of Large Alluvial Rivers: Western Europe*, Wiley, Chichester.

Thorne, C. R., Hey, R. D. and Newson, M. D. (Eds) 1997. *Applied Fluvial Geomorphology for River Engineering and Management*, Wiley, Chichester.

Weston, A. E. 1979. 'The measurement of interactive freshwater and tidal flow in the River Dee, North Wales', *Journal of the Institute of Water Engineering Science*, **33**, 69–79.

Williams, G. P. and Wolman, M. G. 1983. *Downstream Effects of Dams on Alluvial Rivers*, US Geological Survey Professional Paper **1286**.

